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# Correlation of the Thermal Component of the Yield Stress of Body Centered Cubic Metals

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*Prepared for* COMMANDER SPACE SYSTEMS DIVISION

UNITED STATES AIR FORCE

*Inglewood, California*



LABORATORIES DIVISION • AEROSPACE CORPORATION  
 CONTRACT NO. AF 04(695)-169

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### ABSTRACT

The variation of the thermal component of the yield stress,  $\tau^*$ , with temperature for the Groups VA and VIA body centered cubic transition metals has been determined from data reported in the literature. It was found that the temperature dependence of  $\tau^*$  is relatively independent of structure for a purity of  $< 99.98\%$  by weight, but may decrease for higher purity material and for single crystals as compared to polycrystals, in agreement with what had previously been found for iron. By plotting  $\tau^*$  versus the parameter  $(T - T_0)/T_m$ , it was possible to correlate the data for all the b.c.c. transition metals.  $T$  is the test temperature,  $T_0$  the temperature where  $\tau^*$  is first zero, and  $T_m$  the melting temperature. The present results support thermally-activated overcoming of the Peierls-Nabarro stress as the mechanism responsible for the strong temperature dependence of the yield stress in the b.c.c. metals.

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## INTRODUCTION

A correlation has been established for the thermal component of the yield stress of the body centered cubic transition metals in Groups VA and VIA of the Periodic Table. The study which resulted in this correlation was an outgrowth of a previous analysis of data published by various investigators on the effects of temperature on yielding and flow of body centered cubic metals (b. c. c.), Ref. 1.

In the original study, it was pointed out that a number of investigators had attributed the temperature dependence (or thermal component) of the lower yield stress ( $\sigma_{LY}$ ) of b. c. c. metals to the tearing of dislocations from their atmosphere of interstitial atoms (Ref. 2 and 3). However, strong temperature dependence had also been observed for the proportional limit ( $\sigma_P$ ) and the flow stress ( $\sigma_\epsilon$ ), measured at a strain beyond the Luders strain, as shown in Fig. 1. The lattice friction stress ( $\sigma_{00}$ ) in iron was also known to depend strongly on temperature (Ref. 4). In addition, the temperature dependence of the reversible flow stress ( $\sigma_{fl}$ ) for strained electrolytic iron had been found to be independent of strain (Ref. 5). It was concluded from these facts that the proportional limit, lower yield stress, and subsequent plastic flow in b. c. c. metals are controlled by the same mechanism.

Additional data on iron revealed that the purity and crystalline form (i. e., single crystal or polycrystal) also affect the temperature dependence of the yield stress. By plotting the difference between the yield stress at test temperature,  $T$ , and that at  $300^\circ\text{K}$  versus the test temperature, the temperature independent component of the stress was removed. The data points, plotted in this manner, fell into two scatter bands. One of the bands (termed Band A) had a strong temperature dependence and the other, Band B, had a somewhat weaker temperature dependence (though still greater than that generally observed for face centered cubic and close packed hexagonal metals).

Band A represents all data points of polycrystalline materials of low purity (i. e., where  $C + N > 0.01\%$  by wt), and Band B represents the data points of high-purity polycrystals (where  $C + N < 0.01\%$  by wt) and high and low purity single crystals. The results are shown in Fig. 2.

The effect of interstitial content and grain boundaries on the temperature dependence of the yield stress was further examined by plotting the difference between the yield stress of iron at  $78^\circ\text{K}$  and  $300^\circ\text{K}$  versus the impurity content of carbon plus nitrogen. The results showed that the temperature dependence of the yield stress for polycrystalline iron is greatly dependent on the interstitial content up to  $\sim 0.015\%$  by weight, whereas, single crystals exhibited only slight dependence. Above  $0.015\%$  by weight, no additional effect was observed. Thus, it was concluded that the strong temperature dependence of the lower yield stress is associated with the combined effect of interstitial impurities and grain boundaries. A lower temperature dependence results if either is missing.

A graphical comparison was prepared on the effect of temperature on: 1) the lower yield stress ( $\sigma_{LY}$ ) from Fig. 2; 2) the lattice friction stress ( $\sigma_{00}$ ) in material with a  $C + N$  content of  $0.16\%^*$  from Ref. 4; and 3) the reversible flow stress after a strain of  $5\%$  ( $\sigma_{f1}$ ) for electrolytic iron with a  $C + N$  content of  $0.017\%$  from Ref. 5. It is seen in the comparison (Fig. 3) that the data points for  $\sigma_{00}$  and  $\sigma_{f1}$  fell (with one exception) into Band A. Since the values for  $\sigma_{00}$  were obtained by extrapolating  $\sigma_0$  to  $(C + N) \text{ in solution} = 0\%$ , it appears that the total impurity content governs the temperature dependence of  $\sigma_{00}$ , rather than the amount of impurity in solution. It will be noted in Fig. 3 that the value for  $\sigma_{00}$  at  $77^\circ\text{K}$  fell outside Band A. It was suggested that the occurrence may have been the result of twinning, which has been observed by a number of investigators at low temperatures (Ref. 6, 7, and 8).

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\*The amount in solution was only  $0.005$  to  $0.025\%$ .

In conclusion, the initial study showed that:

- 1) The proportional limit ( $\sigma_P$ ), the lattice friction stress ( $\sigma_{00}$ ), and the reversible flow stress ( $\sigma_{fl}$ ) show a temperature dependence similar to that for the lower yield stress ( $\sigma_{LY}$ ).
- 2) The temperature dependence of the flow parameters ( $\sigma_{LY}$ ,  $\sigma_{fl}$ , and  $\sigma_{00}$ ) in polycrystalline iron is determined by the total interstitial content, rather than by the amount of impurity in solution.
- 3) In iron, the presence of both grain boundaries and interstitial impurities is required to give the very strong temperature dependence of the stress normally attributed to b. c. c. metals.

The results of the initial analysis prompted further research to establish a correlation between reported values for the thermal component, or temperature dependence, of the yield stress of all body centered cubic transition metals in Groups VA and VIA of the Periodic Table.



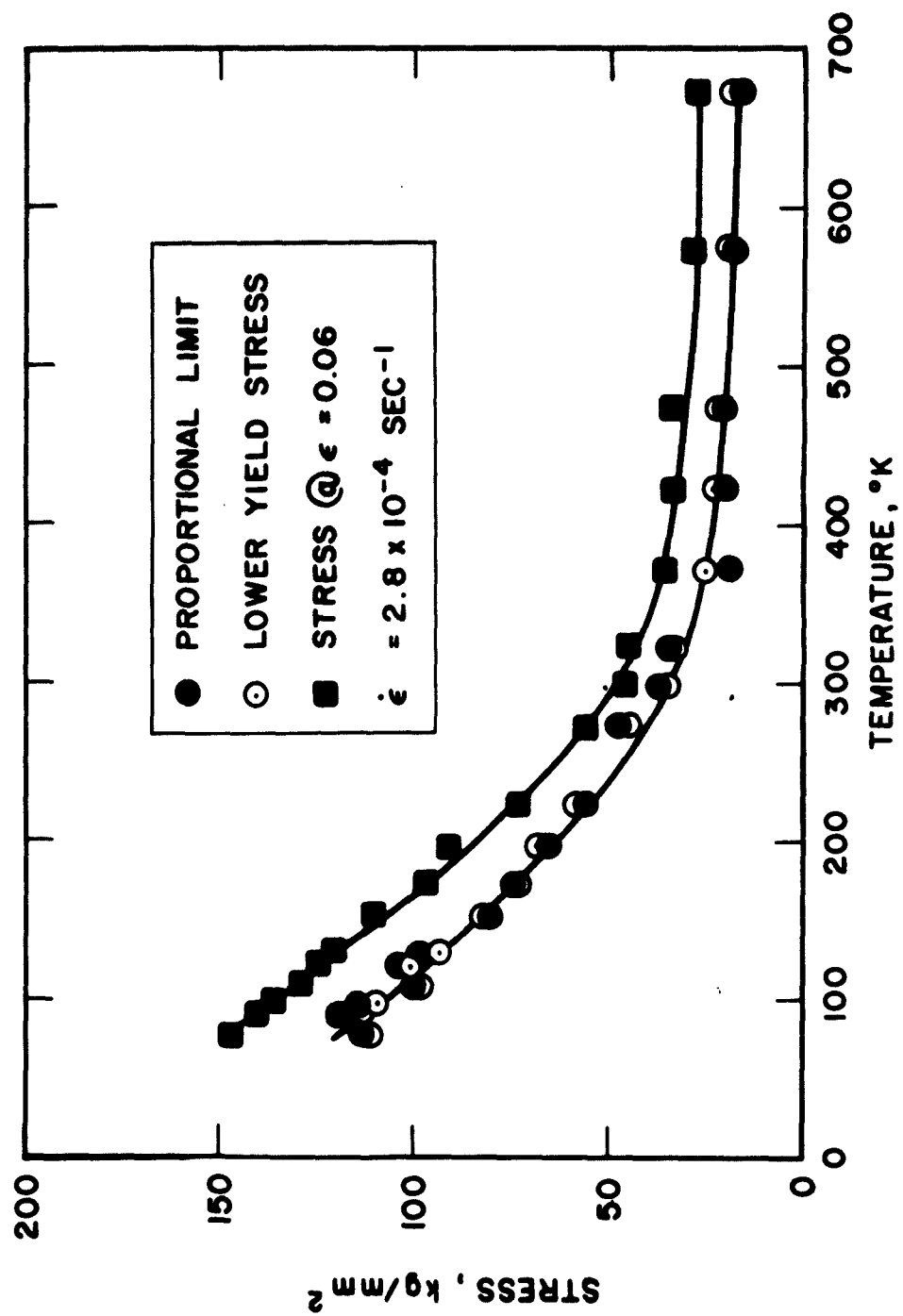


Fig. 1. Effect of Temperature on the Proportional Limit, Yield Stress and Stress After Strain of 0.06 for Molybdenum in Compression

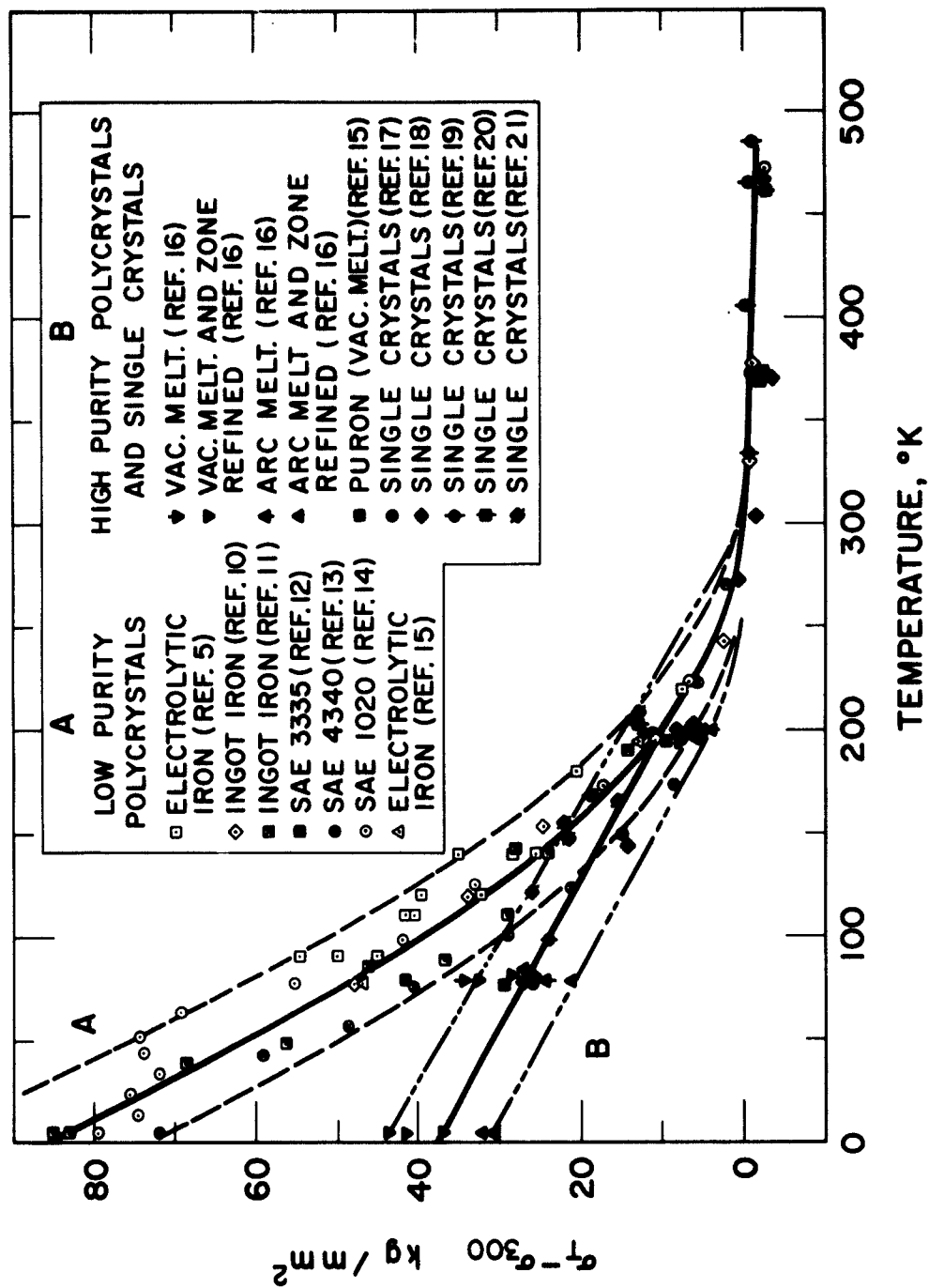


Fig. 2. Effect of Temperature on the Lower Yield Stress of Iron and Several Steels in Tension

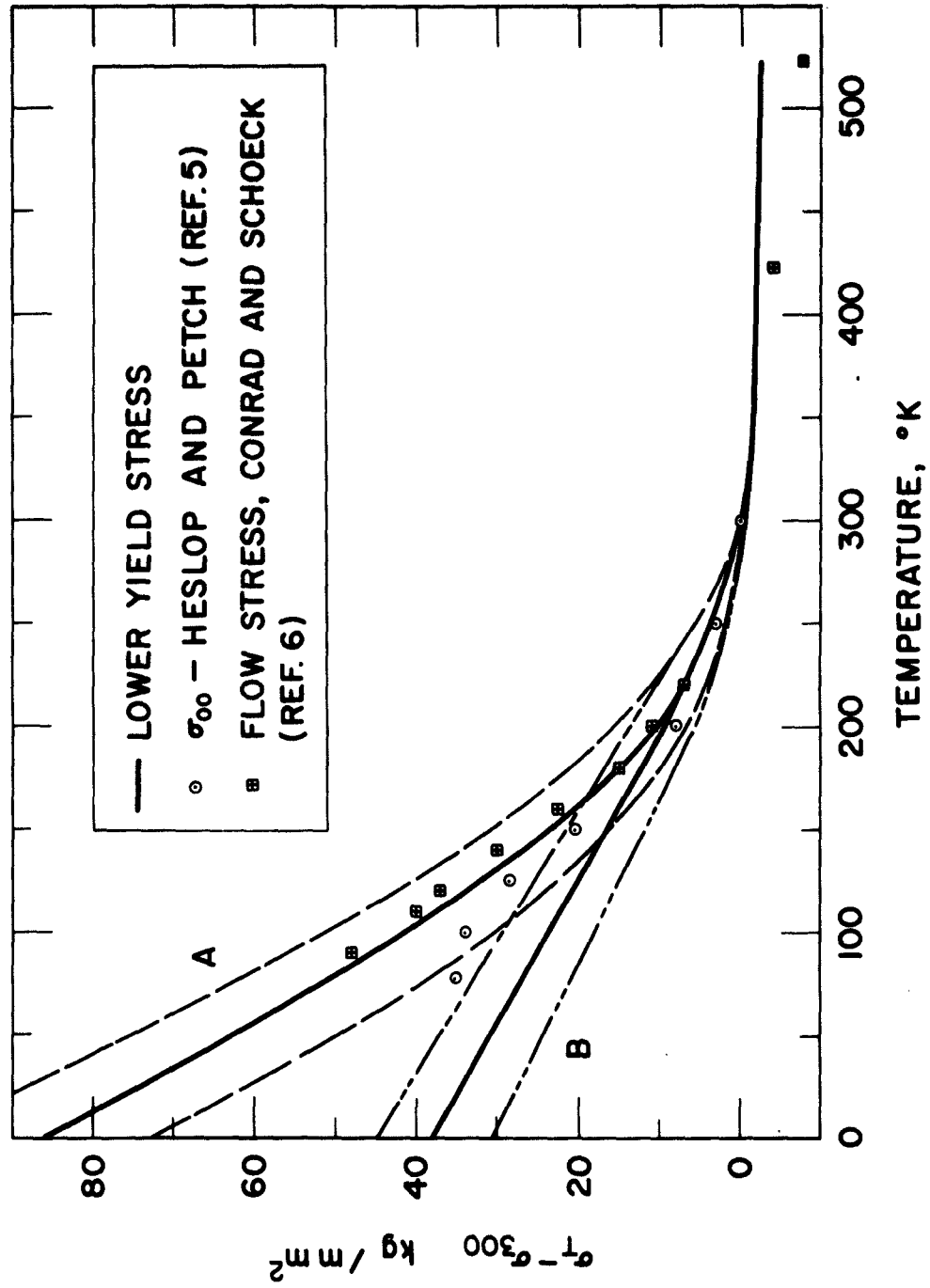


Fig. 3. Effect of Temperature on the Lower Yield Stress,  $\sigma_{LY}$ , the Frictional Stress,  $\sigma_{00}$ , and the Flow Stress,  $\sigma_{f1}$ , of Iron in Tension

## CORRELATION OF THE THERMAL COMPONENT

Figure 4 summarizes the results of the original investigation of iron<sup>†</sup> which formed the basis for the subsequent work in establishing a correlation between the thermal components of the yield stress. The temperature independent component of the yield stress has been removed from consideration in Fig. 4 by plotting the difference between the yield stress at temperature  $T$  and that at  $300^{\circ}\text{K}$  versus the test temperature. The stresses plotted in Fig. 4 through 12 are shear stresses (i. e., one-half of the tensile stress for polycrystalline specimens and the critical resolved shear stress for single crystals).

The thermal component of the yield stress for the b. c. c. transition metals of Groups VA and VIA behaves in a manner similar to that observed for iron, as shown in Fig. 5 through 10. (Supplemental information pertaining to the figures is presented in Table 1.) The similarity in behavior between the b. c. c. transition metals and iron suggests that the temperature dependence of the yield stress of all of the b. c. c. transition metals can be correlated through a parameter such as the melting temperature. Previous attempts at such a correlation have not been completely successful; in fact, they suggest a difference in behavior between the Group VA and Group VIA metals (Ref. 24 and 25). However, in Fig. 11, it is seen that a reasonable correlation exists between all of the b. c. c. transition metals of low purity (<99.98% by wt) when the thermal component of the yield stress ( $\tau^* = \tau - \tau_{\mu}$ ) is plotted versus the parameter  $(T - T_0)/T_m$ , where:

$\tau$  = the applied shear stress taken as one-half of the tensile stress,

<sup>†</sup>Data for zone-refined iron at  $4.2^{\circ}\text{K}$  from Ref. 16 are not included in the figure due to the occurrence of twinning at that temperature. In view of this and other considerations (Ref. 22 and 23), the yield stress for single crystals and high-purity polycrystals (>99.995% by wt) of iron is considered to follow the dashed curve of Fig. 4, rather than as indicated in the initial study.

$\tau_{\mu}$  = the long-range internal stress which is dependent on the structure and proportional to the shear modulus ( $\mu$ ),

$T$  = the test temperature,

$T_0$  = the temperature at which  $\tau$  first becomes equal to  $\tau_{\mu}$ ,

$T_m$  = the melting temperature.

The data points of Fig. 11 were taken from the solid curves of Fig. 4 through 10.  $T_0$  was derived as follows. When  $\tau^*$  is zero, then

$$\tau = \tau_{\mu} = a\mu \quad (1)$$

where  $a$  is a constant. Differentiating Eq. (1) and substituting for  $a$ , one obtains

$$\frac{d\tau}{dT} = \frac{\tau}{\mu} \frac{d\mu}{dT} \quad (2)$$

In the temperature range where the plots of  $\tau^*$  versus temperature are relatively flat, one finds that

$$\frac{1}{\mu} \frac{d\mu}{dT} = 1.5 \text{ to } 3.5 \times 10^{-4} \text{ per } ^\circ\text{K} \quad (3)$$

for the various b. c. c. metals. <sup>†</sup> Further, since the yield stress in this range is approximately 10 to 20 kg/mm<sup>2</sup>, one obtains from Eq. (2)

$$\frac{d\tau}{dT} \approx 5 \times 10^{-3} \text{ kg/mm}^2/\text{ } ^\circ\text{K} \quad , \quad (4)$$

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<sup>†</sup> The variation of modulus with temperature was taken from Ref. 26 and 27.

when  $\tau^* \approx 0$ .  $T_0$  is then obtained by extrapolating plots of

$$\log\left(\frac{d\tau}{dT}\right)$$

versus temperature to a value of  $5 \times 10^{-3} \text{ kg/mm}^2/^{\circ}\text{K}$ . (Refer to Fig. 12.)  
The value for

$$\frac{d\tau}{dT}$$

was obtained by graphical differentiation of the curves in Fig. 4 through 10. The values of  $T_0$  (to the nearest  $50^{\circ}\text{K}$ ) derived in this manner are given in Table 2. It is estimated that the values are accurate to within 10%.

In Fig. 13, it is seen that  $T_0$  is approximately proportional to the melting temperature (i. e.,  $T_0 \approx 0.22 T_m$ ). This agrees with previous observations (Ref. 25 and 28) that the yield stress of the b. c. c. metals shows a relatively temperature-independent region above  $0.20$  to  $0.25 T_m$ .

The fact that the thermal component of the yield stress correlates in this manner suggests that the same dislocation mechanism is rate-controlling in the b. c. c. metals. Furthermore, since the thermal component is independent of structure, one can conclude that this mechanism is overcoming the Peierls-Nabarro stress, i. e., overcoming the inherent resistance of the b. c. c. lattice.

The decrease in stress noted for vanadium, columbium, and tantalum, following the region of relatively constant stress, probably represents the migration of interstitials along with the dislocations.

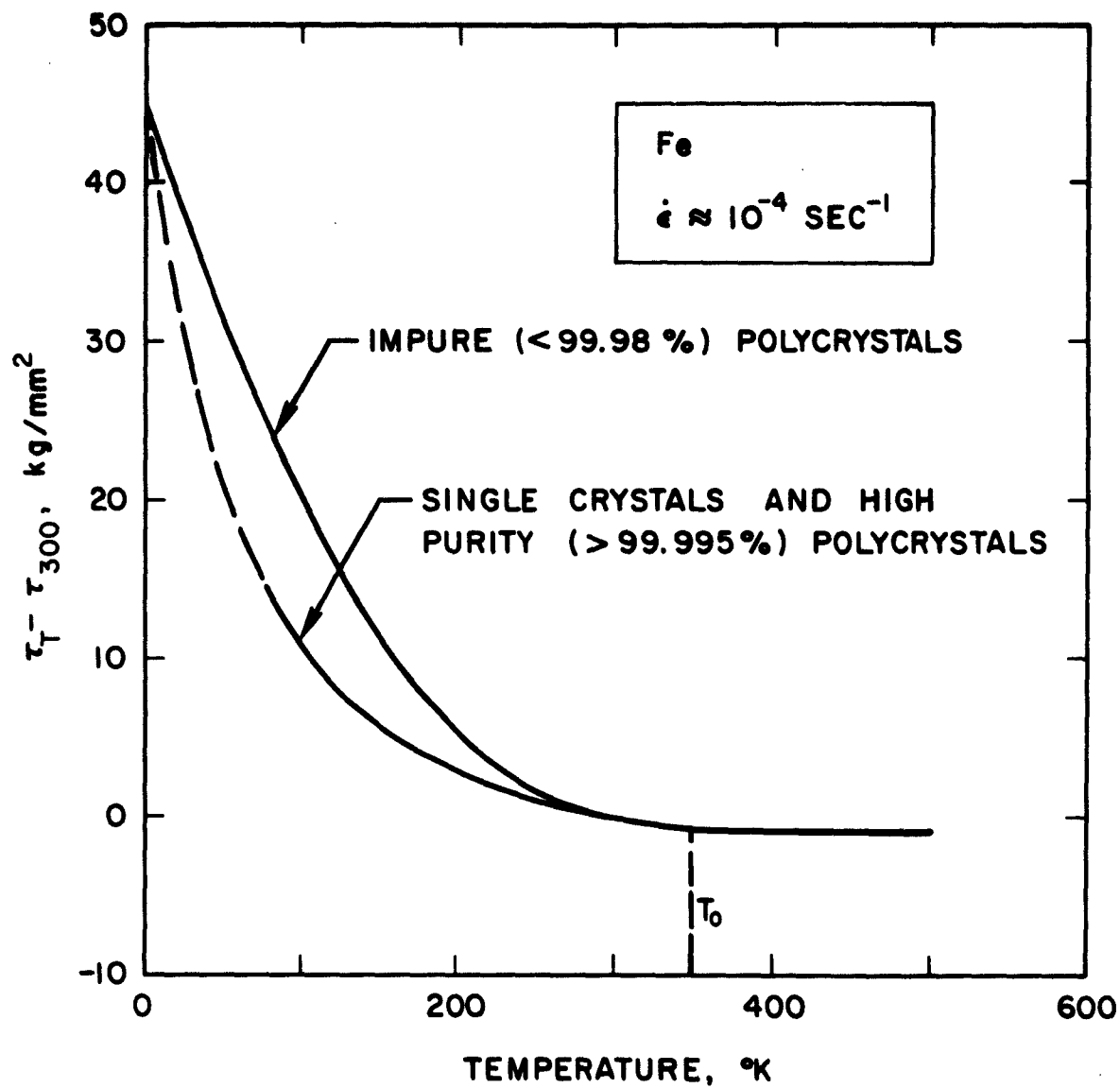


Fig. 4. Summary of Data on the Effect of Temperature on the Thermal Component of the Yield Stress of Iron

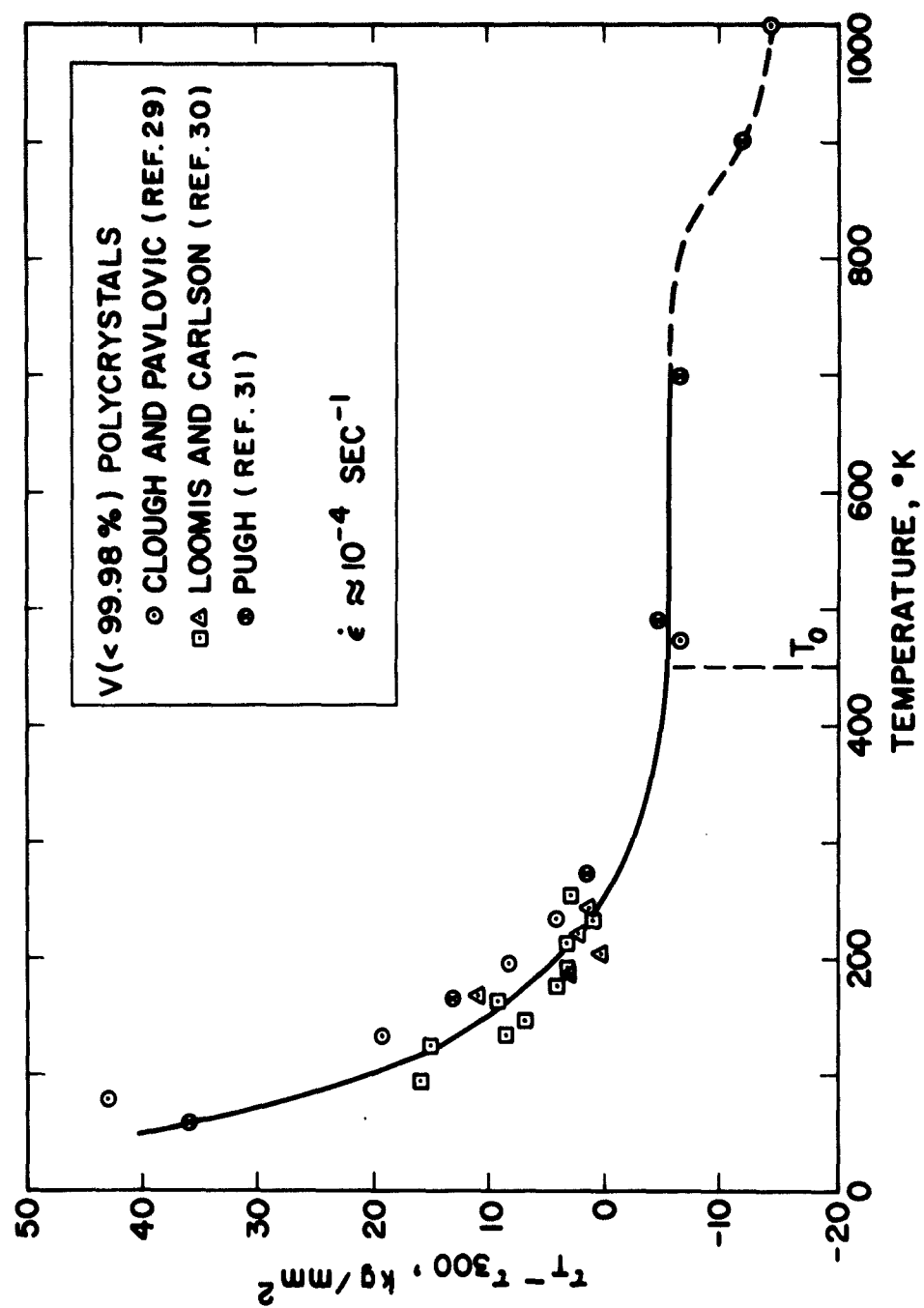


Fig. 5. Effect of Temperature on the Thermal Component of the Yield Stress of Vanadium



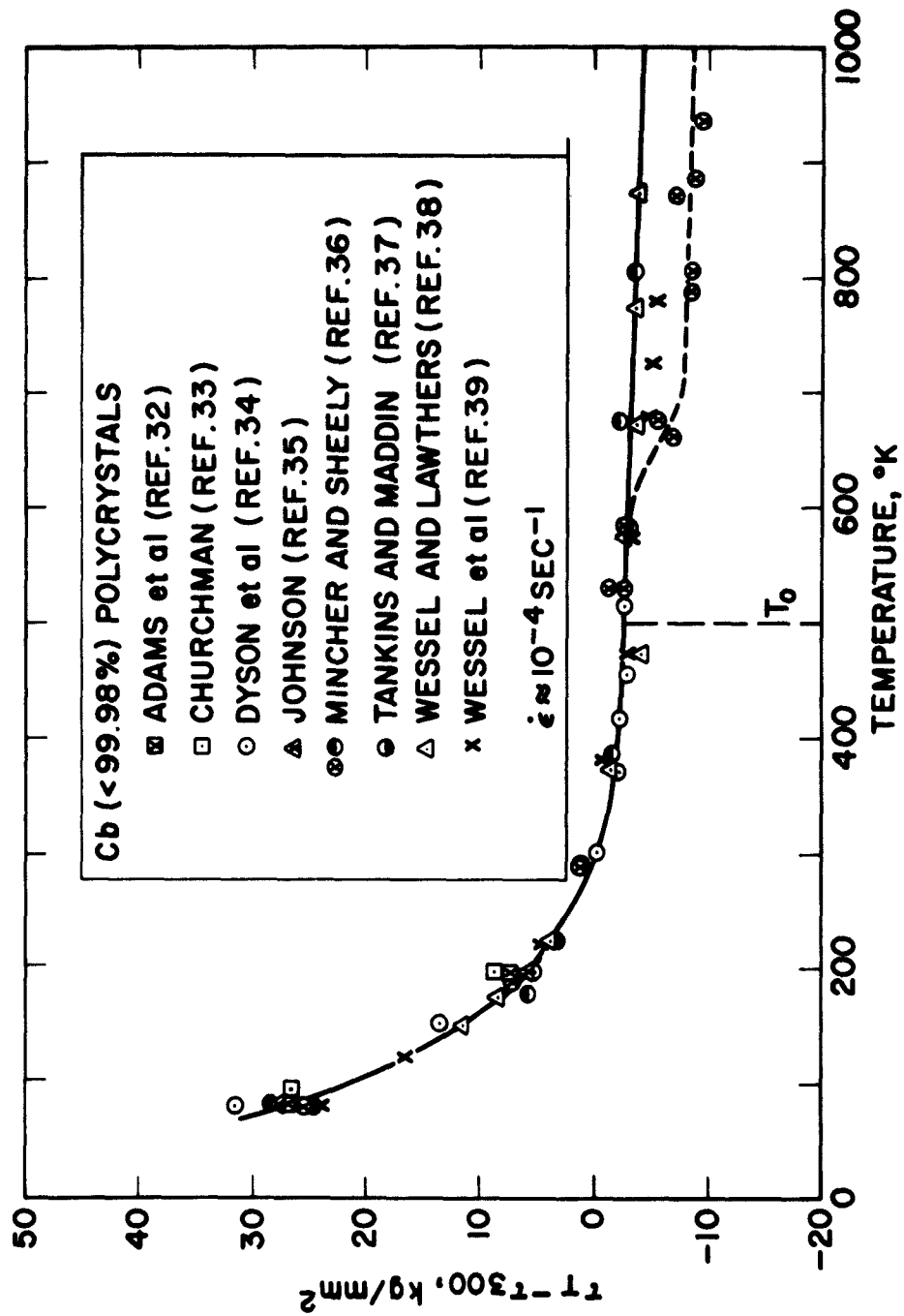


Fig. 6. Effect of Temperature on the Thermal Component of the Yield Stress of Columbium

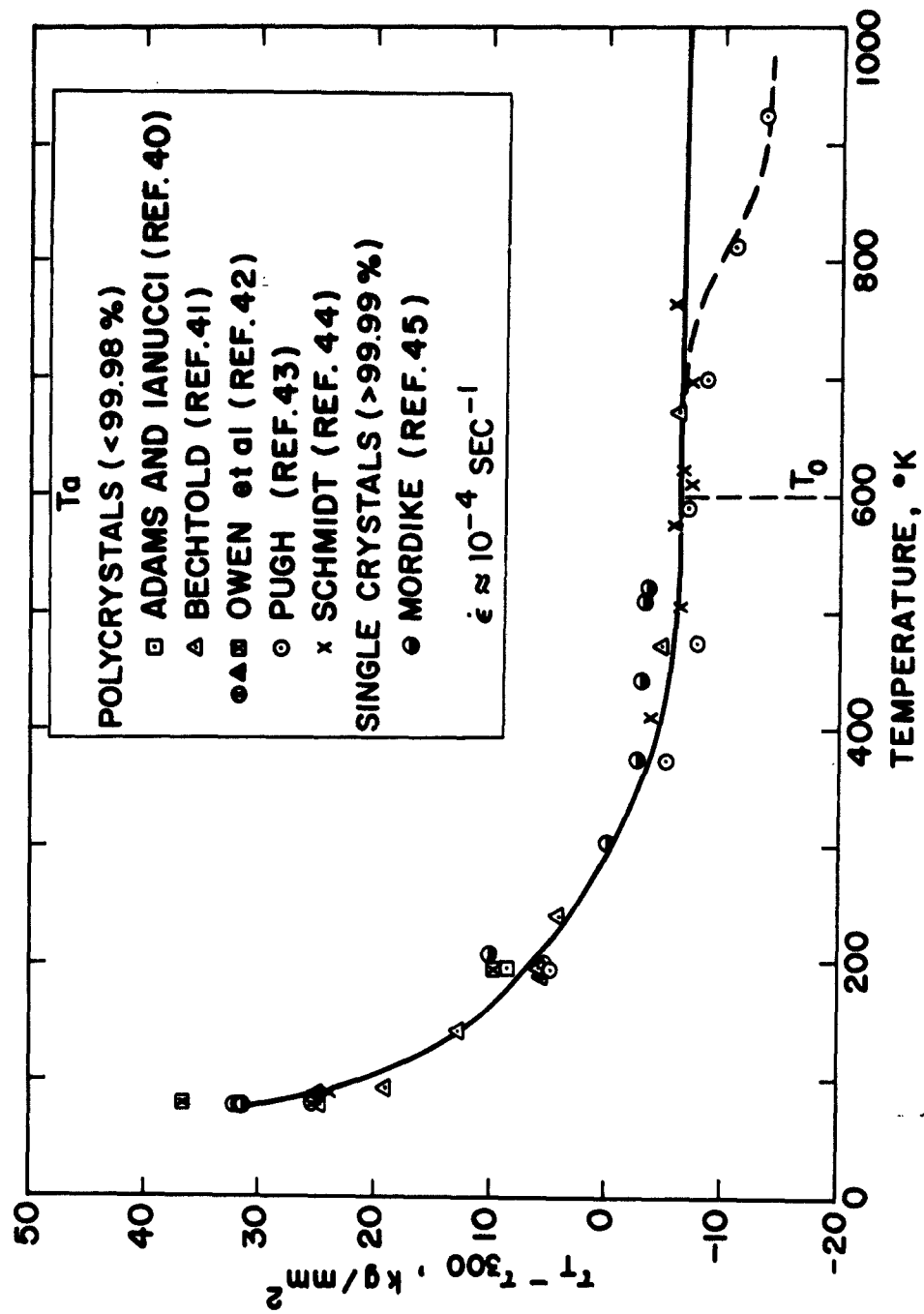


Fig. 7. Effect of Temperature on the Thermal Component of the Yield Stress of Tantalum

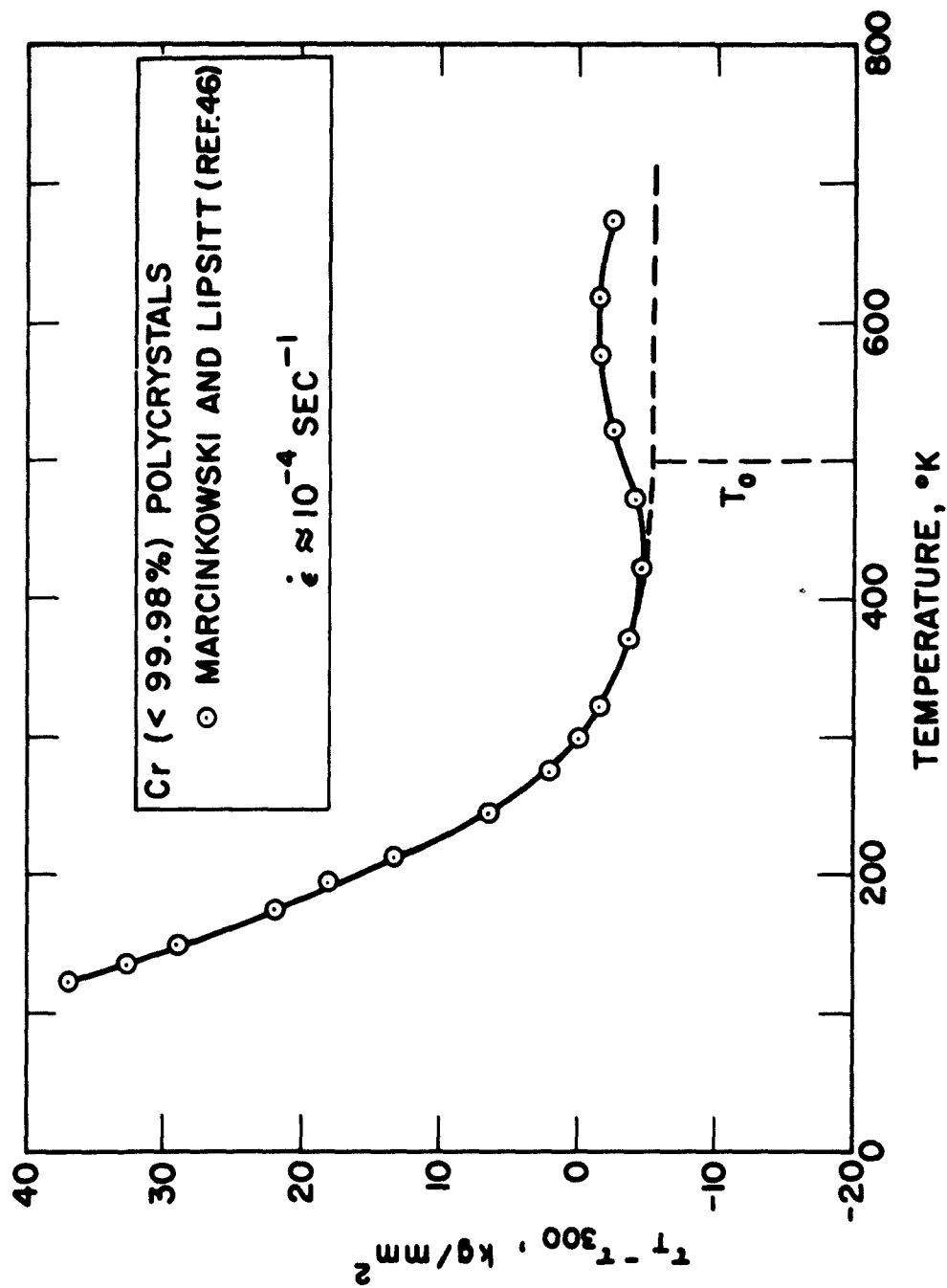


Fig. 8. Effect of Temperature on the Thermal Component of the Yield Stress of Chromium

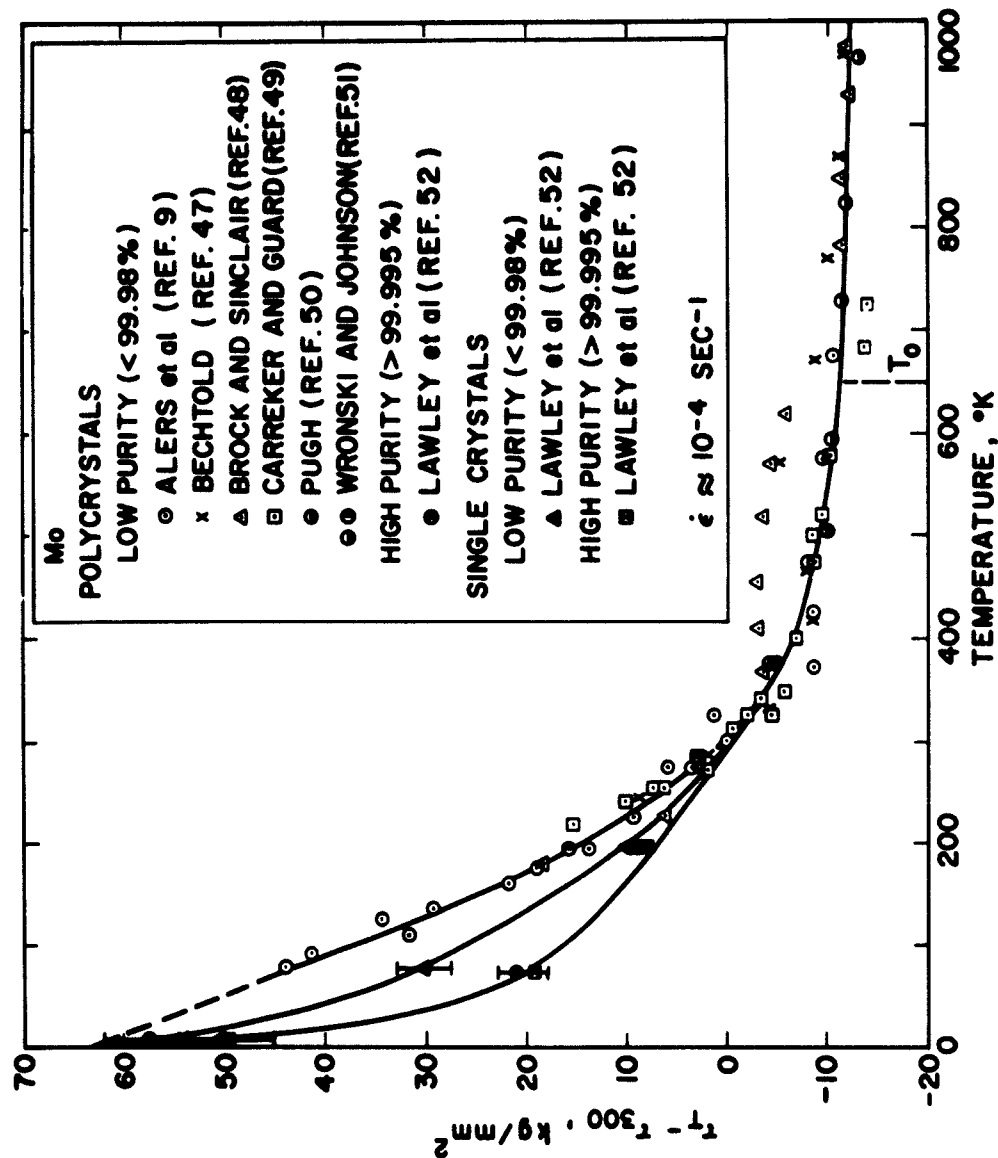


Fig. 9. Effect of Temperature on the Thermal Component of the Yield Stress of Molybdenum

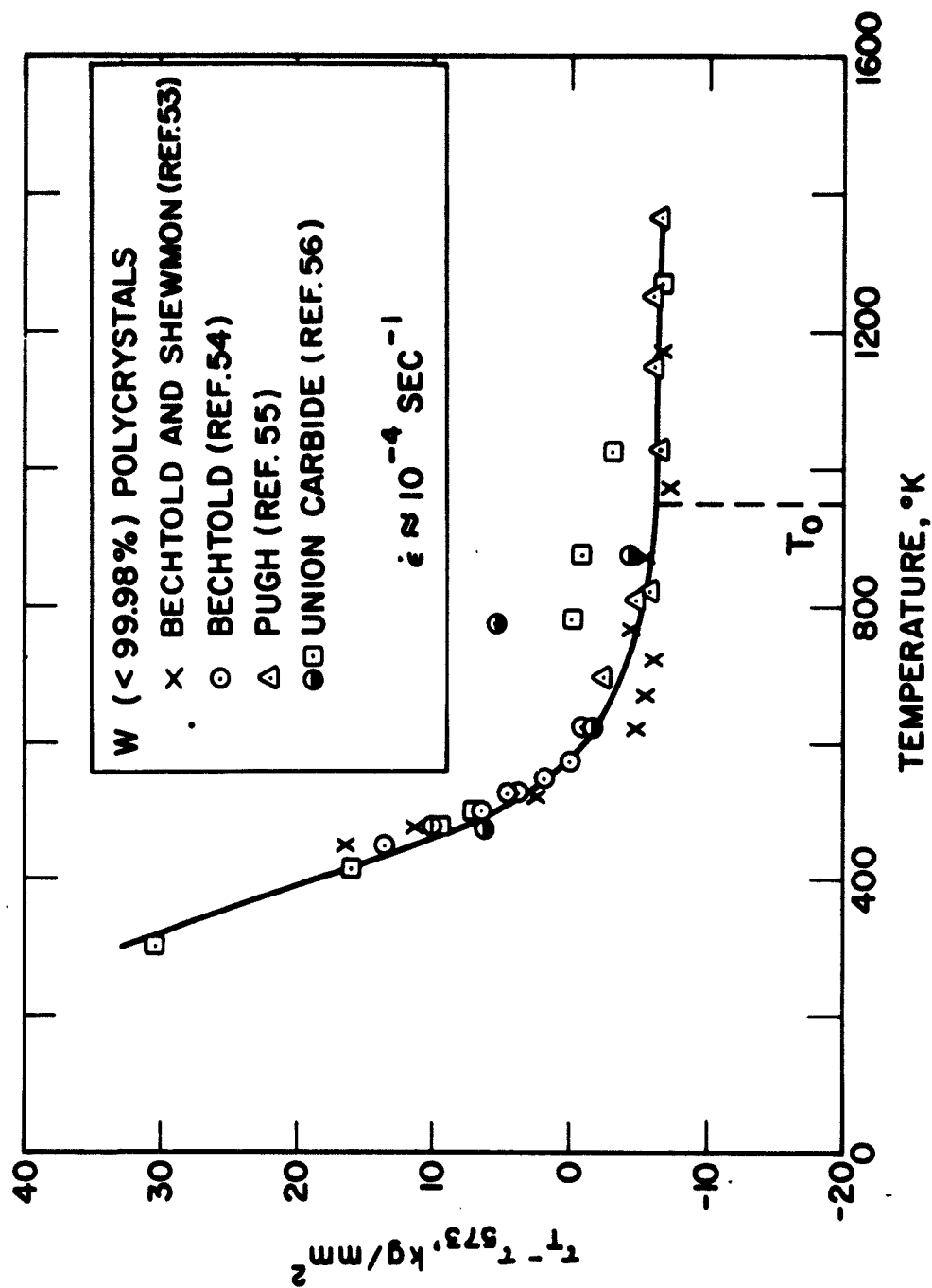


Fig. 10. Effect of Temperature on the Thermal Component of the Yield Stress of Tungsten

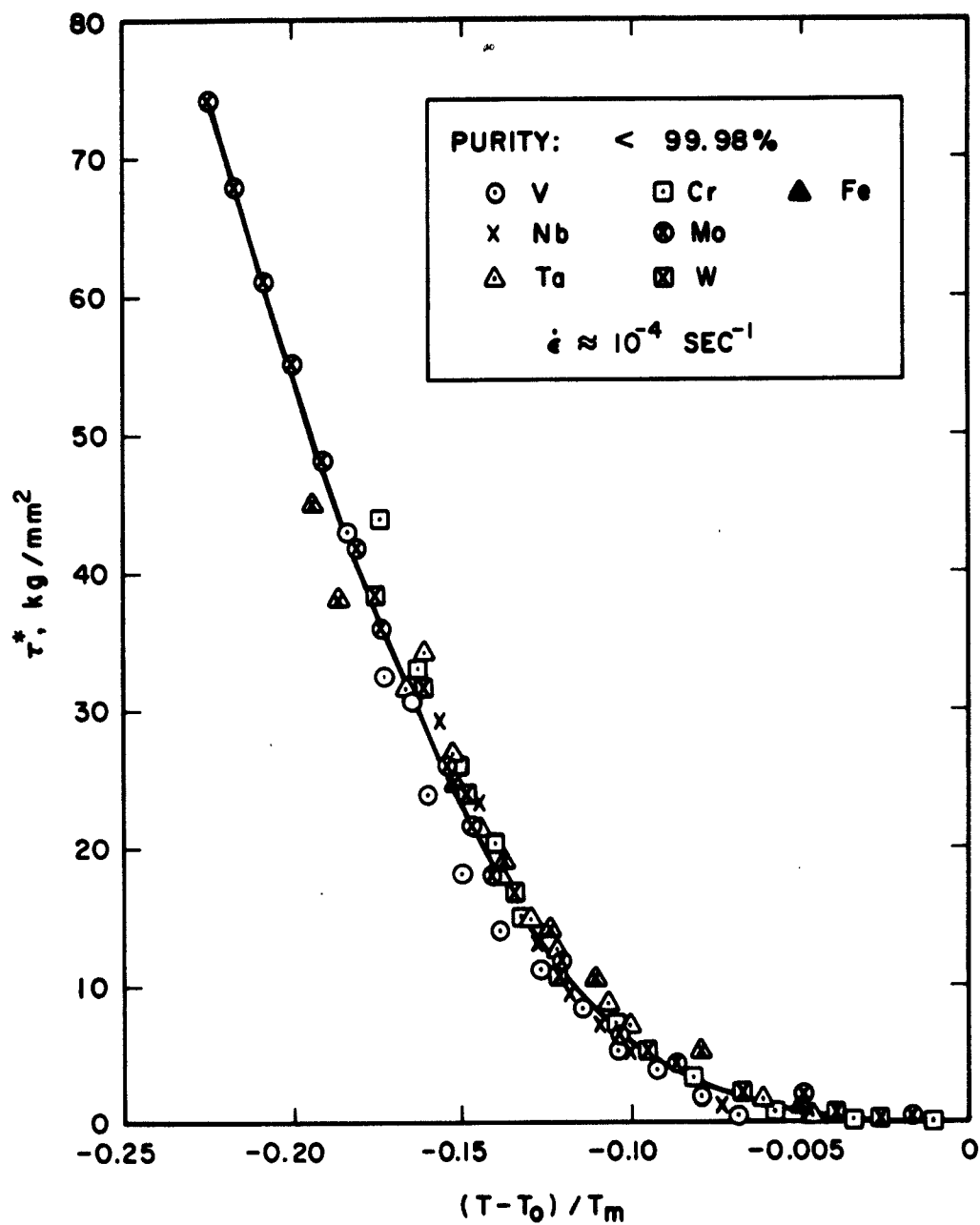


Fig. 11. Correlation of the Thermal Component of the Yield Stress,  $\tau^*$ , with the Parameter  $(T - T_0)/T_m$ , for the B. C. C. Transition Metals

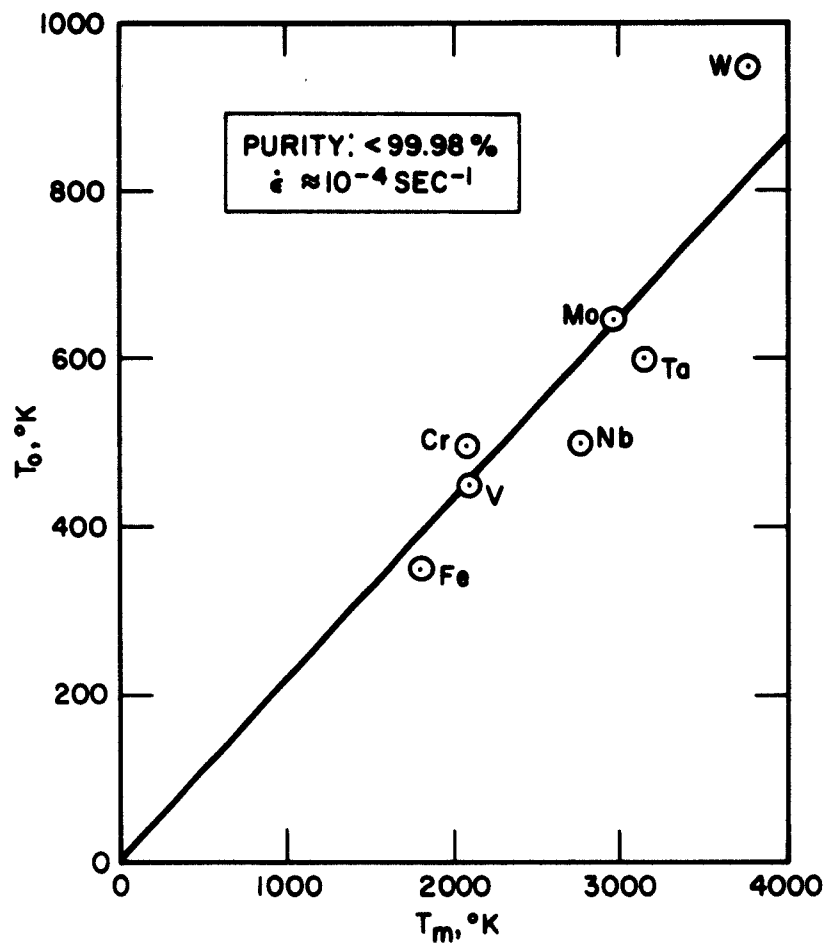


Fig. 12. Variation of  $T_0$  with Melting Temperature,  $T_m$ , for the B. C. C. Transition Metals

Table 1. Information Pertaining to Fig. 5 through Fig. 10

Material <sup>a</sup>	Ref.	Interstitial Content, % by wt				Grain Size, mm	Strain Rate, sec <sup>-1</sup>	Type of Test	Stress Plotted <sup>c</sup>	$\tau_{300}^d$ kg/mm <sup>2</sup>
		C	O	N	H					
VANADIUM	Cal-Red-A. M. Rod	.047	.070	.052	.0043	.1 to .2	$5 \times 10^{-4}$	T	$\tau$ (0.2%)	19.5
	Cal-Red-A. M. Rod	.08	.02	.02	.006	.04	$1 \times 10^{-4}$	T	$\tau$ (0.2%)	7.8
	Iodine Bar-A.M. Rod	.024	.01	.005	.001	.20	$1 \times 10^{-4}$	T	$\tau$ (0.2%)	4.5
	A. M. Sheet	.09	.057	.07	.0004	.03	$15 \times 10^{-4}$	T	$\tau$ (0.2%)	18.4
COLUMBIUM	E. B. wire	.070	.010	.05	.02	.048 to .1414	$2 \times 10^{-4}$	T	$\tau_i$ (LY)	7.0
	Murex wire	—	.05	<.01	—	.013 to .6	$4 \times 10^{-4}$	T	$\tau_i$ (LY)	8.8
	High-purity Sheet	.01	.01	—	—	.014	$.7 \times 10^{-4}$	T	$\tau_{LY}$	8.1
	Murex P. M. Rod	.01	.034	.014	.0014	.037 to .138	$3 \times 10^{-4}$	T	$\tau_i$ (YS)	9.0
	E. B. Rod	.021	.010	.009	.0008	.045	$.8 \times 10^{-4}$	T	$\tau$ (.2%)	7.5
	A. M. Rod	.03	.040	.02	<.001	.024	$.8 \times 10^{-4}$	T	$\tau$ (.2%)	12.0
	P. M. wire	.1	—	—	—	.064 to 3.2	$2 \times 10^{-4}$	T	$\tau_i$ (P)	3.0
	P. M. Rod	.011	.021	.012	—	.25	$10 \times 10^{-4}$	T	$\tau$ (.01%)	9.7
	E. B. Rod	.018	.020	.011	.0001	.09	$1 \times 10^{-4}$	C	$\tau$ (.05%)	8.5

<sup>a</sup>E. B. = electron beam melted; P. M. = powder metallurgy; A. M. = arc melted.

<sup>b</sup>T = tension; C = compression.

<sup>c</sup> $\tau_i$  = extrapolated stress to infinite grain size; LY = lower yield stress; P = proportional limit; CRSS = critical resolved shear stress; YS = yield stress.

<sup>d</sup> $\tau_{300}$  = stress at 300°K.



Table 1. Information Pertaining to Fig. 5 through Fig. 10 (Continued)

Material <sup>a</sup>	Ref.	Interstitial Content, % by wt				Grain Size, mm	Strain Rate, sec <sup>-1</sup>	Type of Test <sup>b</sup>	Stress Plotted <sup>c</sup>	$\tau_{300}$ , <sup>d</sup> kg/mm <sup>2</sup>
		C	O	N	H					
TANTALUM	40	.005	.0082	.0063	.0002	.019 - .889	$10 \times 10^{-4}$	T	$\tau_i$ (LY)	10.8
	41	.0014	.008	.006	-	.047	$3 \times 10^{-4}$	T	$\tau_{LY}$	14.0
	45	.001	.001	<.003	<.001	single crystal	$3 \times 10^{-5}$	C	CRSS	7.3
	42	.0035	.0012	.0012	-	.035 - .111	-	T	$\tau_i$ (LY)	8.2
	42	.0008	.0100	.0014	-	.034 - .345	-	T	$\tau_i$ (LY)	10.1
	42	.0003	.0012	.0096	-	.011 - .056	-	T	$\tau_i$ (LY)	9.9
	43	.02	.0056	.013	-	.037	$15 \times 10^{-4}$	T	$\tau$ (0.2%)	20.2
	44	-	.0016	.0010	.0001	.04 - .06	$8 \times 10^{-4}$	T	$\tau_{LY}$	8.3
CHROMIUM	46	-	<.0200	.0050	.0008	.095	$0.8 \times 10^{-4}$	C	$\tau_{LY}$	12.3
MOLYBDENUM	9	.007	.002	.012	-	.032	$3 \times 10^{-4}$	C	$\tau$ (.01%)	18.2
	47	.014	.0017	.0056	-	.030	$3 \times 10^{-4}$	T	$\tau_P$	16.8
	48	.0054	.0079	.0012	-	.035	$3 \times 10^{-4}$	T	$\tau_{LY}$	10.9
	49	.04	<.003	-	-	.018	$7 \times 10^{-4}$	T	$\tau_{LY}$	21.9

<sup>a</sup>E. B. = electron beam melted; P. M. = powder metallurgy; A. M. = arc melted.

<sup>b</sup>T = tension; C = compression.

<sup>c</sup> $\tau_i$  = extrapolated stress to infinite grain size; LY = lower yield stress; P = proportional limit; CRSS = critical resolved shear stress; YS = yield stress.

<sup>d</sup> $\tau_{300}$  = stress at 300° K.

Table 1. Information Pertaining to Fig. 5 through Fig. 10 (Continued)

Material <sup>a</sup>	Ref.	Interstitial Content, % by wt				Grain Size, mm	Strain Rate sec <sup>-1</sup>	Type of Test <sup>b</sup>	Stress <sup>c</sup> Plotted	$\tau_{300}^d$ kg/mm <sup>2</sup>
		C	O	N	H					
MOLYBDENUM	52	.0013	<.0001	<.0001	<.0001	0.1 - 0.5	$3 \times 10^{-4}$	T	$\tau$ (0.05%)	12.3
	52	.0013	<.0001	<.0001	<.0001	single crystal	$3 \times 10^{-4}$	T	$\tau$ (0.05%)	14.0
	52	.0013	<.0001	<.0001	<.0001	single crystal	$3 \times 10^{-4}$	T	$\tau$ (0.05%)	9.1
	50	.05	.003	.001	.0003	.045	$30 \times 10^{-4}$	T	$\tau$ (0.2%)	22.9
	51	.016	.007	.0185	.0004	.026	$9 \times 10^{-4}$	T	$\tau_i$	5.3
TUNGSTEN	54	.02	-	.008	-	-	$3 \times 10^{-4}$	T	$\tau$ (0.2%)	-
	53	.02	-	.008	-	.026	$3 \times 10^{-4}$	T	$\tau$ (0.2%)	-
	55	.01	.0131	.003	.0001	.045	$3 \times 10^{-4}$	T	$\tau$ (0.2%)	-
	56	.007	.004	.003	.0002	-	$1 \times 10^{-4}$	T	$\tau$ (0.2%)	-
	56	.011	.004	<.001	.0001	-	$3 \times 10^{-4}$	T	$\tau$ (0.2%)	-

<sup>a</sup> E. B. = electron beam melted; P. M. = powder metallurgy; A. M. = arc melted.

<sup>b</sup> T = tension; C = compression.

<sup>c</sup>  $\tau_i$  = extrapolated stress to infinite grain size; LY = lower yield stress; P = proportional limit; CRSS = critical resolved shear stress; YS = yield stress.

<sup>d</sup>  $\tau_{300}$  = stress at 300°K.

Table 2.  $T_o$  and  $T_m$  for B. C. C. Transition Metals

$T_o$  = temperature where  $\frac{d\tau}{dT}$  is  $5 \times 10^{-3} \text{ kg/mm}^2/^{\circ}\text{K}$   
and  $T_m$  = melting temperature

Metal	$T_m, ^{\circ}\text{K}$	$T_o, ^{\circ}\text{K}$
Vanadium	2173	450
Niobium	2741	500
Tantalum	3269	600
Chromium	2148	500
Molybdenum	2883	650
Tungsten	3683	950
Iron	1810	350

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<p>By plotting <math>\tau^0</math> versus the parameter <math>(T - T_0)/T_m</math>, it was possible to correlate the data for all the b.c.c. transition metals. <math>T</math> is the test temperature, <math>T_0</math> the temperature where <math>\tau^0</math> is first zero, and <math>T_m</math> the melting temperature. The present results support thermally-activated overcoming of the Peierls-Nabarro stress as the mechanism responsible for the strong temperature dependence of the yield stress in the b.c.c. metals.</p>	<p>UNCLASSIFIED</p>
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